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Statistical method for the fatigue life estimation of coke drums

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A R T I C L E I N F O

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A B S T R A C T

Coke drums are vertical pressure vessels used in the delayed coking process in petroleum refineries. They are operated under severe thermal–mechanical conditions by cyclic heating and quenching processes, which make them susceptible to damage. To accurately predict the safety lives of coke drums, a statistical fatigue life evaluation method is proposed in this study. To develop this method, thermal–mechanical cyclic fatigue tests of coke drum materials were firstly conducted to obtain strain-life curves, then simplified thermal-elasto-plastic analytical models were developed to calculate maximum equivalent strain amplitudes for global cycling and local hot and cold spot events. Statistical analysis of temperature data on a coke drum shell was also performed to get the probability distributions of the hot and cold spot events. The final statistical fatigue life evaluation model is based on Palmgren-Miner's damage accumulation rule. The fatigue life of a selected coke drum is hereafter estimated according to the maximum equivalent strain amplitudes in both cladding and base plate. The predicted fatigue life of the coke drum is about 5000 operation cycles, which is within the range of operation cycles to the first-through-thickness crack in coke drums, reported by American Petroleum Institute (API) survey. The evaluation methodology developed in this study can be employed to predict the safety lives of coke drums and is expected to be helpful for the design and maintenance of the equipment.

1. Introduction

Delayed coking is one of the main processes for residual oil processing in the petroleum industry. It converts the heavy residual feed stocks into lighter products such as gasoline, gas oil, heavy distillate and coke, which have high economic values. Coke drums are essential equipment in the delayed coking processes, in which the thermal cracking of the heavy, long chain hydrocarbon molecules of the residual oil takes place and the remnant petroleum coke is collected. In their service lives, coke drums are susceptible to cracking and sometimes associated with bulging deformation after several thousands of operation cycles [1,2]. These damages may lead to unexpected failure of coke drums, which interrupt the production and thus result in huge economic losses. Therefore, it is important to conduct reliable lifetime assessment for coke drums.

Coke drums are clad pressure vessels, typically constructed from low alloy carbon steel base plate and clad with stainless steel for resistance to corrosion. The clad steel plate is manufactured by a special hot rolling process, through which a metallurgical bond between the base and clad plates is formed. During the operation, coke drums experience cyclic processing stages including steam testing, vapor heating, oil filling, steam and water quenching, and unheading with temperature fluctuating from ambient to a maximum about 450–482 °C over a time period from 12 to 24 h. The severe thermal cycling results

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in excessive thermal and mechanical stresses in the coke drum shell and its attachment structures. It has been well recognized that low cycle thermal–mechanical fatigue (TMF) is the most common failure mechanism of coke drums and is responsible for the initiation of cracks in coke drums [3]. Therefore, the reliable lives of coke drums should be estimated based on thermal–mechanical fatigue assessment, rather than isothermal mechanical fatigue assessment of the vessels, which was commonly reported in previous works on coke drums.

During the quenching stage of coke drum operation cycle, a high rate of quenching water is injected into the vessel to timely extract the solid coke. The water becomes non-uniform and random channeling flows due to the porous structure of coke mass. Therefore, random local hot and cold spots can be formed on the coke drum shell during the quenching stage. Such hot and cold spot attacks induce significant local temperature differences and gradients, resulting severe local stresses/strains. In our previous work [4], it was indicated that repeated hot and cold spot attacks at the same locations can cause accumulation of ratcheting strain (progressive local bulging) and thus have significant effects on the service life of coke drums. As a result, the hot and cold spot effect should be carefully taken into consideration in the assessment of the fatigue lives of coke drums. It should be noted that such an effect is quite complicated since the locations, the temperature differences between the affected areas and their surrounding areas are most likely in a random nature. Consequently, coke drums suffer various levels of fatigue damage, which could only be counted using statistical modeling theory. In this regard, a statistical fatigue life analysis method for coke drums instead of a deterministic one should be more appropriate.

There have been a few studies on the fatigue life estimation of coke drums. Ramos et al. [5] assessed a coke drum operating in high temperature cyclic service. The fatigue life of the coke drum in their study was estimated through the evaluation of measured strains and temperatures in the middle portion of the vessel. Li et al. [6] performed high temperature fatigue test on the material weld joints between the coke drum body and the skirt, and estimated the safe life of coke drums based on the S–N curves and the maximum equivalent strain amplitude of the connection weld area. These studies shed some lights on predicting the fatigue lives of coke drums. However, they adopted deterministic analysis methods and the fatigue tests conducted were based on uniaxial isothermal fatigue tests without the consideration of the cyclic thermal conditions. To provide a more accurate fatigue life evaluation method, the fatigue tests of the coke drum materials in this study are carried out under thermal–mechanical cyclic loading condition, which represents a similar loading scenario experienced by the coke drums during the operation.

As mentioned before, the hot and cold spot effect in the quenching stage significantly influences the stress and strain levels in the coke drum shell, therefore, should be included in the fatigue life evaluation of coke drums. In order to capture this effect, Ju et al. [4] developed a three-dimensional finite element model to calculate the stresses induced by the hot and cold spots. Zhang and Xia [7] later developed a simplified local stress analysis model for the estimation of hot and cold spot effect on the drum shell. In their model, the hot or cold spot was realized by imposing a temperature difference, either higher or lower, than the temperature of its surrounding medium. Based on the simplified model, the stresses and strains induced by the hot and cold spot effect at both cladding and base plates could be obtained. Besides, it is noted that the temperature differences resulting from the hot and cold spots in every operational cycle are random due to complicated water channel formations inside the porous solid cokes. To the authors' knowledge, the research on the fatigue life estimation of coke drums considering the randomness of hot and cold spot effect has not been reported thus far. How to incorporate the random nature of the hot and cold spot effect in the fatigue life prediction of coke drums is a challenge but the aim of the current research.

In the current work, a statistical fatigue life analysis method will be presented for the coke drums. The development of this method depends on the thermal–mechanical cyclic fatigue test results; the developed simplified thermo-elasto-plastic models and the statistical analysis of temperature data on a coke drum shell. To simulate the loading scenario experienced by the coke drums in service, in-phase thermal–mechanical cyclic loading was applied to the specimens in the designed fatigue tests. The thermal–mechanical cyclic fatigue tests provide strain-life relations of the coke drum materials with mean strain and mean stress effects, thus the fatigue life of the coke drum material could be predicted with any given maximum equivalent strain amplitude and its corresponding mean strain and mean stress. From the simplified models, for global thermal–mechanical cycling and each local hot and cold spot event, the maximum equivalent strain amplitude, the mean strain and mean stress can be computed. The randomness of the hot and cold spot event is considered by obtaining the statistical distributions of the temperature differences between the hot and cold spots and their surrounding medium. To address the effects of general hot and cold spots occurring in overall temperature measuring area of the coke drum and severe hot and cold spots occurring in one specific course of the coke drum, respectively, two statistical distributions are considered in this work. Finally, by combining Palmgren-Miner's cumulative damage rule and probabilities of various loading conditions, the statistical fatigue life evaluation model of coke drums is developed. In this study, the fatigue lives of a selected coke drum under global and various local loading conditions during its service life are estimated using the developed model. This methodology presented is considered to be new and appropriate for the fatigue life prediction of coke drums.

2. Experimental setup and TMF tests on coke drum materials

To simulate complex thermal–mechanical loading condition similarly experienced by coke drums, a thermal–mechanical fatigue (TMF) test system was successfully developed and installed in our lab as shown in Fig. 1. The system mainly consists of a closed-loop servo-controlled hydraulic MTS testing machine, a heating device, a control system, and gripping fixtures. An